

## Application of Nanocomposite Coatings with Different Structural Physical and Chemical Characteristics in Tissue Engineering

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The research covers the results of experimental studies of the effect character of nanocomposite coatings with different physical and chemical parameters (type, roughness, hydrophilic-hydrophobic characteristics) on structural and functional properties (adhesive potential, phenotype, gene expression) of mesenchymal stem cells (MSCs). On the tested nanocoatings ( $\text{Al}_2\text{O}_3$ ,  $\text{ZrO}_2$ ,  $\text{Ta}_2\text{O}_5$ ) the capability of oxide coating  $\text{Al}_2\text{O}_3$  to enrich the *in vitro* cultured bone marrow (BM) with the cells of MSCs phenotype markers as well as to increase the expression rate of *ido* gene in them, which may extend the spectrum of their therapeutic application in clinics, has been found.

**Keywords:** Nanocomposite coatings, Mesenchymal stem cells, *ido* gene.

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### 1. INTRODUCTION

One of the perspective area of implementation of high-tech projects, accumulating biological and medical achievements of the recent decades is nanobiomedicine. In the literature there are reported the questions concerning studying the possibilities of applying nanotechnologies in medicine, in particular tissue engineering [1]. Tissue engineering is conceptually new strategy of treating many diseases and defects of an organism. In its base there is the designing of biological substitutes of tissues and organs. It successfully combines in its methods the application of novel techniques of molecular-cell biology and recent achievements of material science. An example of tissue engineering allowing the induction of regenerative processes in the damaged organs and tissue of living organism is the use of cell scaffolds or matrices, determining the structure and geometry of new tissues. In discussion of the questions related to the application of biomaterials used for implants-carriers (scaffold-techniques) the attention is focused to the need of investigating their different characteristics. An alternative to tissue engineering is the development of effective biomedical technologies of material obtaining *in vivo* as cell suspension with the aim of their application in clinical practice.

Rushing investigations in the field of cell and tissue engineering has demanded the intensifying of the works on introducing the novel technologies, methods, approaches, including the use of different on their origin nanomaterials [1, 2].

Even now there has been proved the possibility of controlling the functional state of cells by modifying the surface of nanocomposite coatings whereon they are cultured [3]. There was demonstrated the effect of physical and chemical parameters of the matrices (titanium and its alloys, ruthenium, niobium, different polymers) on functional characteristics of cultured osteoblasts, fibroblasts, macrophages [4]. However in spite of numerous reports on studying the behaviour of different cells when culturing on various nanocarriers in respect of the stem compartment cells the existing data are apparently insufficient. In cell-tissue therapy of special attention are mesenchymal stem cells (MSCs). The demand of MSCs as a corrector of many pathological states is quite logic and based on their capability of manifesting the immune modulating potential [2]. Functional status of these cells is determined by the ability to migration into damaged sites of a recipient's organism, production of cytokines there (IL-6, IL-7, IL-8, IL-11, IL-12, IL-14), growth factors and many other regulatory molecules with the aim of implementation (locally or distantly) of regenerative processes and minimization of immune inflammatory reactions. It is commonly known that during MSC culturing *in vitro* they manifest a high plasticity potential. To implement it the certain culturing conditions and standard media providing differentiation towards the lineage needed have been designed. The modification of surface coatings whereon they are cultured may obviously also be additional and quite significant factor of controlling the functional status of stem elements. In some reports special attention is paid to studying the surface energy of coatings, its dispersion and polar components and their effect on cell cultures [4]. There was demonstrated for instance the correlation between surface properties of coatings and proliferative potential of fibroblasts: high indices of surface energy and fraction polarity stimulated the proliferation of the studied cells.

In this connection the research aim was investigation of the effect peculiarities of nanocomposite coatings with different physical and chemical parameters

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on structural and functional characteristics (adhesive potential, phenotype, gene expression) of cultured on them cells with MSCs features.

## 2. MATERIALS AND METHODS

In the present study the samples were glass substrates (Petri dishes), uncoated and oxide-coated ( $\text{Al}_2\text{O}_3$ ,  $\text{ZrO}_2$  (MS) magnetron-sputtered and  $\text{Ta}_2\text{O}_5$  (EB) e-beam-evaporated) with different roughness parameters – 20, 200 and 400 nm. The  $\text{Al}_2\text{O}_3$  (MS) coatings deposition was performed in a high-vacuum pumping system with base pressure of about  $10^{-3}$  Pa. The main process parameters were: magnetron discharge power 1-8 kW, oxygen source power 1 kW, deposition rate  $8 \mu\text{m} / \text{hour}$  [5]. The  $\text{Ta}_2\text{O}_5$  films evaporation process was carried out at initial vacuum of  $7 \times 10^{-4}$  Pa, operational mode vacuum of  $3 \times 10^{-3}$  Pa, anode current of 50 mA and calculated evaporation power of 350 W [6]. The deposition rate under these conditions was  $28 \text{ nm} / \text{min}$ .

The surface roughness was measured by means of a Hommel T-2000 profilometer and the surface topography was estimated by AFM (Quesant Instrument Corporation, USA). The coatings' structure was investigated by means of XPS and XRD. The X-ray photoelectron spectroscopy measurements were carried out using an ESCALAB MkII (VG Scientific) electron spectrometer at a base pressure in the analysis chamber of  $5 \times 10^{-8}$  Pa ( $1 \times 10^{-6}$  Pa during the measurement), using an  $\text{Al}\alpha$  X-ray source (excitation energy  $h\nu = 1486.6 \text{ eV}$ ).

Other parameters, such as surface free energy (SFE), its polar and dispersion components and fractional polarity were determined by means of the Wu and Owens-Wendt-Rabel-Kaelble methods. The contact angles were measured on a Kruss K12 Tensiometer at  $20^\circ\text{C}$  [6].

BM cells were obtained from femoral bones of CBA/H mice and cultured in Iscove's medium containing 10 % FBS, 50 units / ml penicillin, 50 units / ml streptomycin in 3 cm glass Petri dishes without or with studied nanocoatings with seeding density of  $0.5 \cdot 10^6$  cells /  $\text{cm}^2$  at  $37^\circ\text{C}$ , 5 %  $\text{CO}_2$ . Adhesive potential of BM cells was assessed in 48 hrs of culturing according to the routine method [7]. Cell cultures were visually controlled using light phase contrast microscope (Axiovert 25, Zeiss, Germany).

BM cells were passaged with density of  $0.5 \cdot 10^4$  cells /  $\text{cm}^2$  when achieved sub confluent monolayer. At the end of each passage the cells were taken-off with trypsin-EDTA solution (Sigma) according to the standard methods [8], inactivated with the medium containing 10 % FBS, washed-out and their structural and functional characteristics were estimated.

The MSCs phenotypical characteristics were determined by a FACS Calibur cytofluorimeter using fluorochromal monoclonal antibodies to CD73, CD105, CD106, CD90, CD44 structures.

The data obtained with cytofluorimetric analysis were statistically processed with WinMDI 2.8.

The expression rate of *ido* gene in cultured MSCs (passage 1 and 2) on various substrates was assessed by PCR with the stage of reverse transcription (PCR-RT) during an hour after thawing [9] on the presence of

their amplicons. Total RNA was isolated by means of Diatom RNA Prep 100 (Isogene Lab Ltd, Russia) from  $1 \times 10^5$  cells of each sample. The resulted mixture of nucleic acids was treated with DNase I according to the instructions of the producer ("Syntol" Ltd, Russia). RT reaction was set using random-oligonucleotides and revertase (M-Mlv) (R&D institute, "Reverta L", Russia). The primers to the studied genes were designed using the data base "GenBank" (NCBI BLAST, USA): *ido*-NM\_008324.1 and were synthesized at "Medbioservis Ltd" (Kiev, Ukraine). The amplification products were detected with capillary electrophoresis in chip analyzer ("Agilent" 2100, USA).

The amount of transcripts of the studied targets was compared on the base of relative quantitative estimation of amplification products. In brief, there were prepared consecutive ten-fold dilutions of initial cDNA preparation from each the sample studied. To every dilution there was added a reactive mixture and the amplification was performed. The less target consequences were in initial preparation, the earlier (i.e. at smaller dilutions) amplifications stopped. The dilution logarithm ( $\lg$ ) cDNA served as the index of expression rate of the investigated genes. The results were levelled in respect to the expression rate of *beta actin* gene (housekeeping gene) (NM\_007393.3). Reactive mixture with no cDNA was a negative control.

The findings were statistically processed with Student's method using MS Excel software.

## 3. RESULTS AND THEIR DISCUSSION

Receptor repertoire of cells represents a complicated system due to which the cells interact each other, structures of intercellular space and finally implement numerous functional activities. One of the main places in a wide spectrum of membrane receptors is taken by the cell adhesion molecules. There is noted that the surface relief acts as the factor modulating an adhesive cell potential [4].

The influence of coatings' deposition and treatment conditions on BM adhesive potential was studied. The adhesive potential of BM cells was statistically and significantly different depending on substrate materials. The best results were obtained on the glass and glass /  $\text{Al}_2\text{O}_3$  (MS) surface. The statistical difference between cell adhesive and survival parameters depending on surface roughness in the range 20-400 nm was observed. The cell adhesion decreases with the rise of surface roughness parameters in the range 20-400 nm.

The structure of  $\text{Al}_2\text{O}_3$  (MS) and  $\text{ZrO}_2$  (MS), magnetron sputtered and  $\text{Ta}_2\text{O}_5$  e-beam evaporated thin films was investigated by means of XPS and XRD methods. X-ray diffraction profiles of  $\text{Al}_2\text{O}_3$  (MS),  $\text{ZrO}_2$  (MS), and  $\text{Ta}_2\text{O}_5$  (EB) as deposited coatings demonstrate the amorphous nature, no peaks were observed. The structural analysis of  $\text{Al}_2\text{O}_3$  (MS) and  $\text{ZrO}_2$  (MS) oxide coatings by means of XPS method was performed. The photoelectron spectra of  $\text{Al}_2\text{O}_3$  (MS) and  $\text{ZrO}_2$  (MS) oxides demonstrate that oxide coatings have a strong stoichiometric composition with binding energy peaks  $E(\text{Al}2p) - 74. \text{ eV}$ ,  $E(\text{O}1s) - 531.3 \text{ eV}$  for  $\text{Al}_2\text{O}_3$  (MS) films. The binding energy peaks  $E(\text{Zr}3d) - 182.4 \text{ eV}$ ,  $E(\text{O}1s) - 530.2 \text{ eV}$  for  $\text{ZrO}_2$  (MS) coatings were observed.

The surface free energy SFE and its polar and dispersion parts, fractional polarity were estimated by Wu method for two liquids system and by Owens-Wendt-Rabel-Kaeble' methods for liquid system:  $\alpha$ -bromonaphthalene- formamide-ethylene glycol-diiodomethane- glycerol-water. The surface free energy changes but is not dependent from the surface roughness parameters in the range 20, 200 and 400 nm. The surface free energy was in the range 52-53 [mN/m] for Al<sub>2</sub>O<sub>3</sub> (MS), 48-51 [mN/m] for ZrO<sub>2</sub> (MS), 41-44 [mN/m] for Ta<sub>2</sub>O<sub>5</sub> (EB) coatings. The results allow the separating of the influence of roughness and surface free energy effects on the regularities of cell/nanomaterial interactions.

The results presented in Fig. 1 demonstrate the dependence of adhesive properties of BM cultured cells both on coating type and surface roughness (20, 200, 40 nm) whereon it was applied. The reduced adhesive potential of BM cells was shown with a rise in embedding roughness.

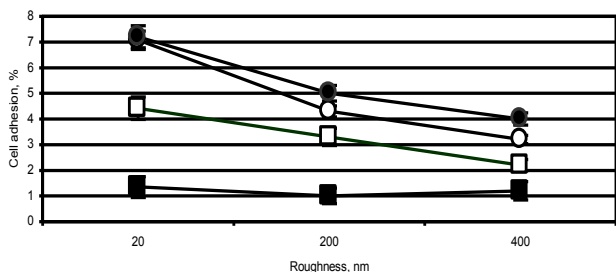


Fig. 1 – Adhesive potential (percents) on various substrate materials with roughness parameters within the range of 20-400 nm after 2 days' culturing: (●) glass, (○) glass / Al<sub>2</sub>O<sub>3</sub> (MS), (◐) glass / ZrO<sub>2</sub> (MS), (◑) glass / Ta<sub>2</sub>O<sub>5</sub> (EB)

Percent of adhesive cells to glass with Al<sub>2</sub>O<sub>3</sub> coating was the highest one, and the lowest one was that with Ta<sub>2</sub>O<sub>5</sub>. Taking into account that in addition to topography of substrate surface the cell adhesion is also affected by their hydrophobic-hydrophilic characteristics (Table 1) [10], one can conclude that the highest hydrophilic properties are inherent to Al<sub>2</sub>O<sub>3</sub> coating. The Ta<sub>2</sub>O<sub>5</sub> coating demonstrates the least value of surface energy and more hydrophobic origin. So, it is evident that the cell adhesion is affected both by roughness rate and hydrophobic-hydrophilic characteristics of the coatings.

By means of cytofluorimetric research method we have estimated the content of cells with MSCs phenotype markers: CD73<sup>+</sup>, CD106<sup>+</sup>, CD105<sup>+</sup>, CD90<sup>+</sup>, CD44<sup>+</sup> in BM culture, passaged on glass (control) and on glass with Al<sub>2</sub>O<sub>3</sub> coating and roughness of 20 nm (experiment) (Fig. 2), demonstrating the highest adhesion to BM cells.

Table 1 – Contact angles (water) and values of surface energy of coatings

No	Samples	Contact angles with water (hydrophilicity), grad	Complete surface energy (interval for different roughness values) [mN/m]
1	Glass control	34-36	60-62
2	Glass / Al <sub>2</sub> O <sub>3</sub>	47-52	52-53
3	Glass / ZrO <sub>2</sub>	52-57	48-51
4	Glass / Ta <sub>2</sub> O <sub>5</sub>	61-65	41-44

It has been established that CD73<sup>+</sup>, CD105<sup>+</sup> and CD106<sup>+</sup> cells cultured on Al<sub>2</sub>O<sub>3</sub> after the 1<sup>st</sup> passage was in 1.4-1.5 times higher, after the second it was in 1,2-1.6 times higher if compared with the corresponding to each passage control (glass). The increased content of CD73<sup>+</sup>, CD105<sup>+</sup> and CD106<sup>+</sup> cells cultured on Al<sub>2</sub>O<sub>3</sub> at the second passage was statistically and significantly higher if compared with the 1<sup>st</sup> one. This fact strongly testifies to the capability of Al<sub>2</sub>O<sub>3</sub> coating to selectively enrich the cultures with BM cells, expressing the MSCs markers.

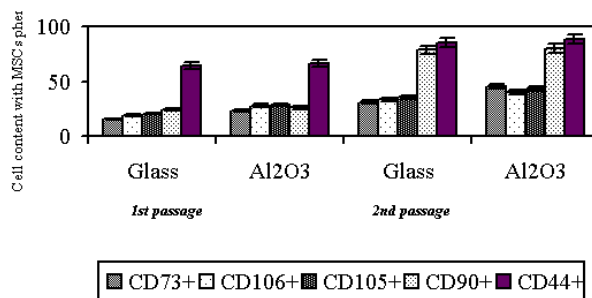


Fig. 2 – Content of cells with MSCs phenotype markers when culturing BM on glass with Al<sub>2</sub>O<sub>3</sub> coating and without it

One of the key characteristics of MSCs is their immune modulating activity [11], implementation of which is related to *ido* gene expression in these cells. Namely to this gene belongs the key role in activation of immune system suppressor link. In this connection in the studied MSCs the expression of *ido* gene was assessed.

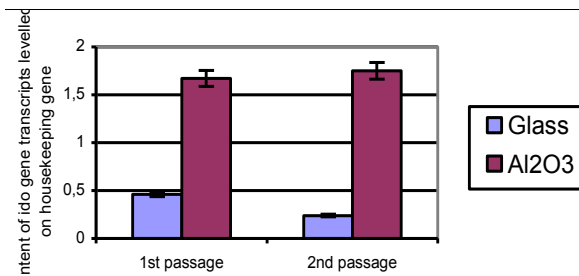


Fig. 3 – Semi-quantitative analysis of *ido* gene expression in MSCs cultured on various matrices

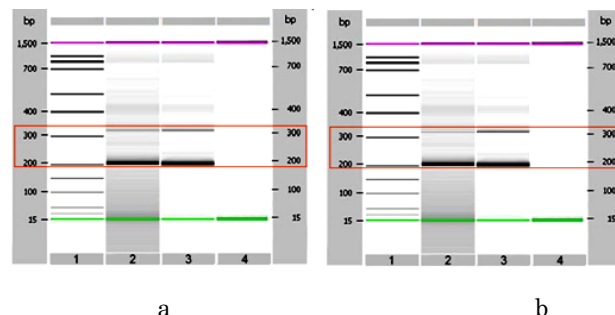


Fig. 4 – Detection of *ido* gene transcripts in MSCs (a – 1<sup>st</sup> passage, b – 2<sup>nd</sup> passage) cultured on different matrices. *Ido* gene (upper marker), house-keeping gene (lower marker); groups: 1 – fragment length marker, 2 – glass, 3 – Al<sub>2</sub>O<sub>3</sub> (20 nm), 4 – blank control

The data presented in Fig 3 and 4 testify to the increased content of transcripts of *ido* gene in MSCs after their culturing on Al<sub>2</sub>O<sub>3</sub> nanocoating after the 1<sup>st</sup> passage in 3.6 times and in 7 times after the second one if compared with the those cultured on glass. It is important that after the second passage the expression rate of *ido* gene in the cultured on glass MSCs reduced twice. The fact of involvement of the embedding into activation in MSCs of *ido* gene expression responsible for the production of IDO enzyme is an interesting one not only from the point of view of fundamental studies but also the widening of spectrum of their clinical application.

#### 4. CONCLUSION

Our data demonstrate that the cell adhesive potential is different for various oxide coatings deposited by magnetron sputtering and e-beam evaporation. The best results were obtained in the case of magnetron-

sputtered oxide coatings with minimal roughness within the range of 20-400 nm, the intermediate values of the surface free energy within the range of 50-60 mN / m and the bulk of SFE polar components and fractional polarity.

The possibility of directed modification of structural and MSCs functional characteristics by culturing substrates has been proved. In particular, it has been found the capability of Al<sub>2</sub>O<sub>3</sub> oxide coating applied to a glass substrate with 20 nm roughness to selectively enrich the cultures of BM cells with MSCs phenotype markers, as well to increase the expression rate of *ido* gene in them.

The established fact of the rise of the content of *ido* gene transcripts in MSCs after culturing on Al<sub>2</sub>O<sub>3</sub> coating focuses to their possible use when treating the pathologies of immune genesis.

### Использование нанокompозитных покрытий с различными физико-химическими характеристиками в тканевой инженерии

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В работе представлены результаты экспериментальных исследований характера влияния нанокompозитных покрытий с различными физико-химическими параметрами (вид, шероховатость, гидрофильно-гидрофобные характеристики) на структурные и функциональные свойства (адгезивный потенциал, фенотипия, экспрессия генов) мезенхимальных стромальных клеток (МСК). Из всего спектра апробированных нанокompозитных покрытий (Al<sub>2</sub>O<sub>3</sub>, ZrO<sub>2</sub>, Ta<sub>2</sub>O<sub>5</sub>) установлена способность оксидного покрытия Al<sub>2</sub>O<sub>3</sub> обогащать культивируемый *in vitro* костный мозг (КМ) клетками с фенотипическими маркерами МСК, а также повышать степень экспрессии в них гена *ido*, что может расширять спектр их терапевтического применения в клинической практике.

**Ключевые слова:** Нанокompозитные покрытия, Мезенхимальные стволовые клетки, Ген *ido*.

### Використання нанокompозитних покриттів з різними фізико-хімічними характеристиками в тканинній інженерії

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У роботі представлено результати експериментальних досліджень характеру впливу нанокompозитних покриттів з різними фізико-хімічними параметрами (тип, шорсткість, гідрофільно-гідрофобні характеристики) на структурні й функціональні властивості (адгезивний потенціал, фенотипія, експресія генів) мезенхімальних стромальних клітин (МСК). Из усього спектра апробованих нанокompозитних покриттів (Al<sub>2</sub>O<sub>3</sub>, Zr<sub>2</sub>, Ta<sub>2</sub>O<sub>5</sub>) встановлена здатність оксидного покриття Al<sub>2</sub>O<sub>3</sub> збагачувати культивованій *in vitro* кістковий мозок (КМ) клітинами з фенотипічними маркерами МСК, а також підвищувати ступінь експресії в них гена *ido*, що може розширювати спектр їхнього терапевтичного застосування в клінічній практиці.

**Ключові слова:** Нанокompозитні покриття, Мезенхімальні стовбурові клітини, Ген *ido*.

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